Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary

Appendix H

Development of an Ecological Model to Predict *Vallisneria americana* Michx. Densities in the Upper Caloosahatchee Estuary: MFL Update

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Summary

The density of *Vallisneria americana* Michx. is estimated using a numerical model developed for the upper Caloosahatchee Estuary. The density is estimated based on responses to light, salinity and temperature at two sites within the upper estuary. Monthly field monitoring of *V. americana* density and water quality parameters has been conducted at these sites since 1998. The model is calibrated based on measured *V. americana* densities, water temperature, and transparency at each station for the period 1998-2001. Daily salinity input is estimated from flows generated by hydrodynamic modeling. Daily incident PAR was obtained from a continuous recording station in Estero Bay. Long–term computations for *V. americana* are developed using predicted salinity regimes from both the 95 base scenario (Pre-CERP) and the D13R (Post-CERP) scenario.

Background

V. americana Michx. in the upstream fresh and brackish water portion of the Caloosahatchee Estuary has been identified in the "Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary" (SFWMD, 9/00 Draft) as a key species to be protected against significant harm. The proposed approach for determining the minimum flows and levels (MFLs) described in this document included the development of daily growth rate algorithms for *V. americana* relating changes in shoot density with salinity. Because the growth model presented was not intended to reproduce the annual cycle of *V. americana* growth or abundance, the shoot density was "reset" each year to a specified constant value. Additionally, salinity was the only environmental variable considered in this *V. americana* growth model. While a scientific review panel endorsed the approach of utilizing *V. americana* as an environmental indicator to establish MFLs, they identified areas where further work was required to validate the MFL. In their final review report, the scientific panel stated that the "*V. americana* approach should be refined, improved and made more robust" (Edwards et al., 2000). The primary criticisms stated by the review panel in the proposed *V. americana* model included:

1. using salinity as the global limiting factor to *V. americana* survival and growth,
2. the lack of variability in spatial and demographic factors,
3. the lack of variability in salinity input regimes,
4. setting annual shoot recovery densities to constant values.

Specifically the review panel recommended that an energetically based *V. americana* model be developed to allow prediction of the complete annual cycle of growth, reproduction, senescence, and overwintering with consideration for multiple environmental factors. Additionally, it was recommended that a hydrodynamic model be utilized to provide salinity input to the *V. americana* model thus permitting the evaluation of a wide range of salinity regimes on SAV growth and survival.

Model Description

A mechanistic, process based ecological model has been developed to investigate growth responses of *V. americana* to varying environmental conditions in the upper Caloosahatchee Estuary. Due to the limited amount of time available for development and calibration, the model presented here is in the preliminary stages of development and future modifications are anticipated. The model consists of a system of 3 simultaneous differential equations (finite difference), one for each of three state variables, solved by Euler numerical integration with a time step of 1 day. State variables represented in the model are the following: total mass, number of shoots and number of blades. The domain of the model is a spatially averaged $1m^2$ single layer water column. Forcing functions are water temperature, incident PAR, secci disk depth, and salinity. The water column is modeled as a non-stratified, homogeneous layer. A conceptual model (**Figure H-1**) illustrates the core processes that control plant growth and abundance in the model.

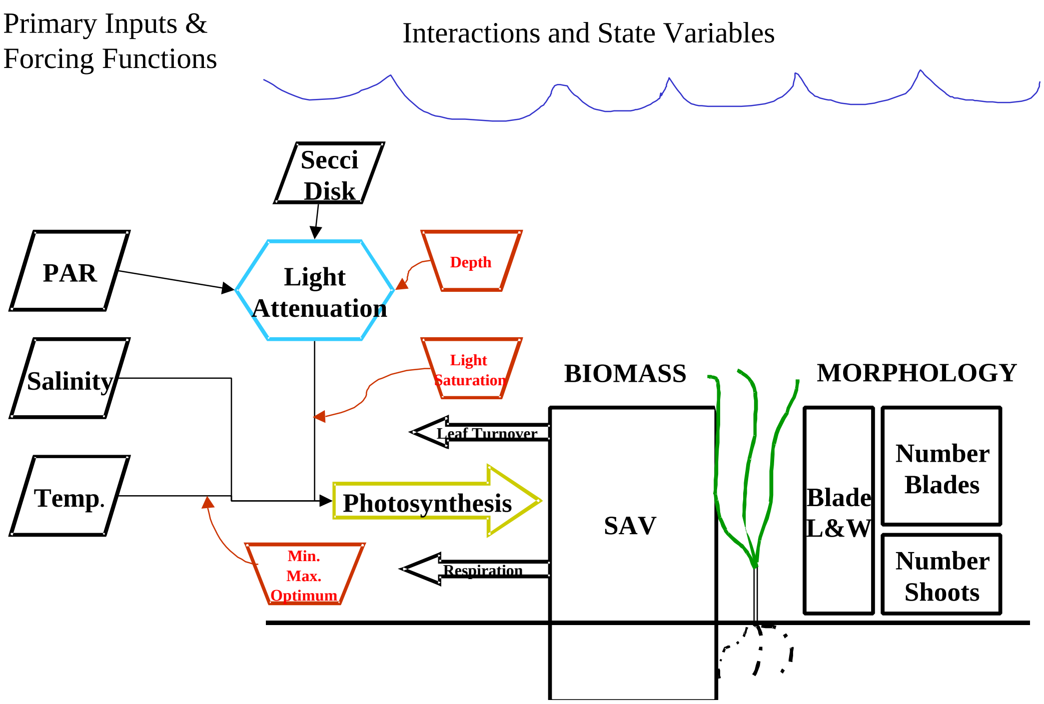


Figure H-1. Conceptual *V. americana* Model for the Upper Caloosahatchee Estuary

State Variable Equations

The equations for mass (g dry weight Carbon/m^2), blade (number of blades/m^2) and shoot density (number of shoots/m^2) were all formulated similarly for each of the state variables. The equation is parameterized for each state variable and repeated three times in the model. The discussion herein shows the equations for blade density. The basic equations are the same for the remaining state variables with a simple substitution of these variables. The equation representing blade density is:

Blade Density (t) = Blade Density (t-dt) + Productivity – Loss

Where:

Productivity = *f* (Blade Density, Salinity, Temperature, Light)

and

Loss = *f* (Senescence, Stress Mortality, Respiration)

Loss

Senescence is considered seasonal and is triggered by day and temperature cues, which are based on both observations in the Caloosahatchee Estuary and the four-year calibration data set. Losses from respiration and stress mortality are temperature dependent and have the following form:

$$(\text{Stress Mortality Coefficients} * \text{Respiration Coefficient}) * (\text{Blade Density}^2) * [0.63*\exp^{(0.092*\text{water temperature})}].$$

Stress mortality terms include a separate coefficient for light and salinity. They are utilized only when conditions fall below tolerance levels for light or salinity. The cues for these coefficients are currently based on the calibration data set. It is anticipated that this algorithm will be refined with the quantification of these stresses from a recent mesocosm experiment (Hunt et al., 2002). If conditions are not outside the tolerance levels, only the base-line respiration coefficient is used in the calculation.

Productivity

Maximum productivity is multiplied by a series of reduction factors that range from 0-1, with 1 representing productivity at optimal environmental conditions and 0 representing conditions that prevent productivity. The reduction factors include the effects of salinity, light, and temperature. Maximum productivity is a density – dependent, self-limitation term determined by calibration that represents the carrying capacity of the environment. Relative growth effect relationships for salinity, light and temperature were developed based on field data, experimental studies using *V. americana* obtained from the Upper Caloosahatchee Estuary, and from information reported in the literature (**Table H-1)**.

Table H-1: Summary of Productivity Variables

VARIABLE	INPUT DATA	RELATIONSHIP	PARAMETERS REQUIRED	SOURCE
Salinity	Salinity, Water-Temperature	Graphical	Growth rate at different salinities for two different temperature ranges (corresponding to wet /dry seasons)	Doering et al., 1999
Light	Incident PAR Secci Disk Depth Water Depth	P/I curve	Ik = 200 μE/m^2*s	Harley and Findlay, 1994: Reported Range 100-279
Temperature	Water-Temperature	Empirical equation (O'Neill et al.,1972)	Q10 = 2 Optimum Temp. = 33 ^{o}C Maximum Temp.= 50 ^{o}C	Wilkinson, 1963

Salinity Effect

V. americana is a salt-tolerant freshwater species that often occurs in the fresh, oligohaline and mesohaline reaches of estuaries in the Northeastern and Southeastern United States (Bourn, 1932; Lowden, 1982). Salinity is an important environmental variable regulating the growth and distribution of *V. americana* in the upper Caloosahatchee Estuary (Doering et al., 1999). Relationships were developed relating relative growth to salinity in the range of 0 to 15 based on mesocosm studies using *V. americana* obtained from the Caloosahatchee Estuary (Doering et al., 1999). These researchers report two different rates based on wet season or dry season experiments. A combined salinity effect was developed in the model for shoots and blades based on these data and differentiated in the model according to incubation temperatures **(Figure H-2)**.

If the water temperature is > 25 ^{o}C then the salinity effect formulated for the wet season is used and if the water temperature is < 25 ^{o}C then the salinity effect formulated for the dry season is used.

Light Effect

The central role of light availability for submerged aquatic vegetation (SAV) has been demonstrated in numerous, field, laboratory, and modeling studies. Changes in water clarity can impact density, depth distribution and species able to grow in a given area. *V. americana* is generally considered light adaptable as it acclimates rapidly to increasing light and efficiently uses low light (Titus and Adams, 1979; Meyers et al., 1943; Harley and Findlay, 1994**)** However, its limited elongation potential may be a disadvantage in deep turbid water (Barko et al., 1984; 1991) and water clarity may an important factor regulating growth and survival especially for seedlings or immature rosettes (Kimber et al. 1995).

The light available for photosynthesis is modeled based on a simple linear photosynthetic versus irradiance (P/I) relationship (Blackman, 1905). In the models present formulation, the amount light reaching the bottom at any given location is assumed to be the amount of light available for photosynthesis. It is recognized that this is a conservative formulation most appropriate for small immature plants and likely underestimates the amount available for mature established plants with leaves extending into the water column.

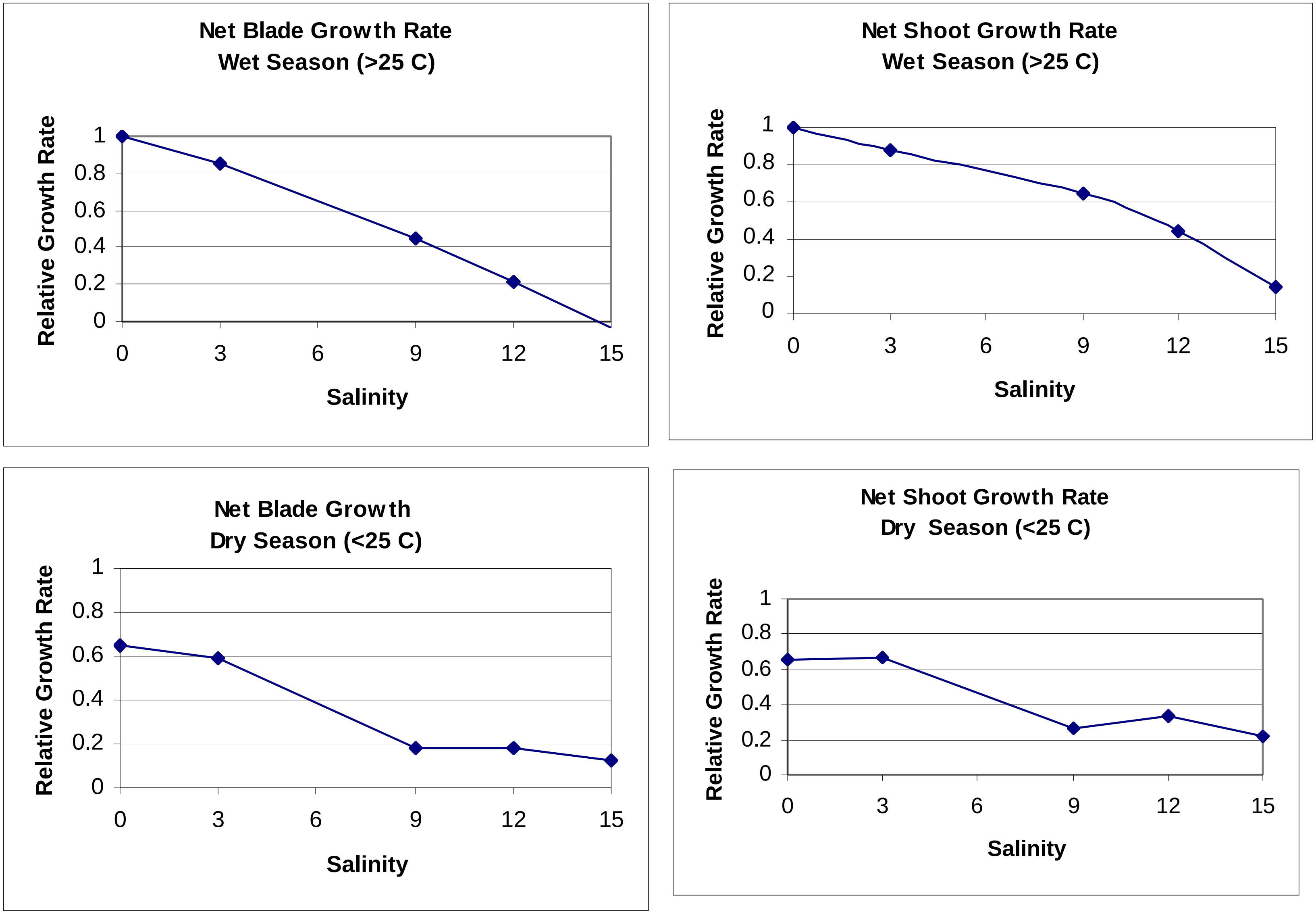


Figure H-2: Combined Salinity Effect for Shoots and Blades.

The amount of light reaching the bottom is determined by the following computation:

$$\text{Bottom PAR} = [\text{PAR}*(1-\text{Surface Reflectance})]*\exp^{(-Kd*\text{Bottom Depth})}$$

where:

surface reflectance = 0.10

and:

Light attenuation = 1.65/secci disk depth.

The relationship for light attenuation (kd) and secchi disk depth is an average conversion based on measurements made by 8 independent researchers (Giesen et al., 1990) valid in the range 0.5 to 2.0 meters (USEPA, 1992). Differences in conversion factors lead to small changes (5% discrepancy) in the determination of light attenuation in very turbid waters. Additionally researchers have suggested that use of secchi disk may not provide accurate estimates of light attenuation in highly colored waters (Dennison, 1990). The model does not differentiate between the various components that cause reduced availability (i.e. color, suspended solids, algae) which may influence the productivity of *V. americana* in different ways. Colored water absorbs the various wavelengths of water differently and algal blooms block sunlight used for photosynthesis. Suspended solids in the water column also physically block the penetration of irradiance through the water column. In addition suspended particles may be harmful when deposited on leaf surfaces by reducing light transmission and possibly blocking gas and nutrient exchange. Large amounts of suspended particles may change the depth and bury existing beds of submerged vegetation. All of these factors are possible and may play a slightly different role in reduced light in the upper Caloosahatchee Estuary at any given time. Contingent on the availability of additional information, it is anticipated that algorithms will be developed to individually represent these components. The calculated bottom PAR is then used to calculate the effect of light changes to relative growth by the following:

$$\text{Light Effect} = \text{Bottom PAR} / I_k$$

Light saturation (I_k) is set at the fixed value 200µE/m^2/s. When bottom PAR is greater than I_k then light effect is assumed to be 1 (optimal available light). The effect of any possible photoinhibition is not considered in this formulation. Additionally, it is assumed that P/I relationship is static and does not change with varying environmental factors. However, P/I curves may vary with depth and season for seagrasses (Drew, 1978; Dawes and Tomasko, 1988) and specifically for *V. americana* (Harley and Findlay, 1994). Recent mescosm experiments (Hunt et al., 2002) indicates that the P/I relationship for *V. americana* in the Caloosahatche Estuary may also change with salinity and plant age. Other factors, which may influence photosynthesis at a particular light level include: the age of the leaves, the orientation of the leaves with respect to the light field, and the psysiological health of the leaves (Fourqurean and Zieman, 1991). It is anticipated that the light relationships for the model in the future will be formulated to include dynamic conditions for salinity and plant age.

Temperature Effect

Temperature changes primarily influence growth of SAV over predictable seasonal cycles. In the upper Caloosahatchee Estuary water temperature ranged from 15 ^{o}C during winter months to 32 ^{o}C in summer months during the period 1998 - 2001. Assuming other conditions are appropriate for growth, *V. americana* can be observed throughout the year, with small rosettes persisting during the winter months. Consistent with the southern ecotype of *V. americana* reported by Smart and Dorman (1993), no over-wintering buds (turions) have been reported for *V. americana* in the Caloosahatchee Estuary. The effect of temperature on relative growth is modeled using the following equation (O'Neill, 1972):

$$kt = kmax U^{x} e^{(XV)}$$

where:

$$U = (Tmax-T) / (Tmax-Topt)$$

$$V = (T-Topt) / (Tmax-Topt)$$

$$X = (W^{2} (1+(SQT(1+40/W))^{2}) / 400$$

$$W = (Q10-1)*(Tmax-Topt)$$

In this formulation kt is the rate of process at temperature T, and kmax is the rate of process at the optimum growth temperature (Topt). In the model kmax is 1, Q10 is 2, optimum growth temperature (Topt) is 33 ^{o}C, and the upper lethal temperature (Tmax) is 50 ^{o}C (Wilkinson, 1963).

It is important to consider that there are varying temperature growth ranges (minimums to maximums) reported for *V. americana* (Barko et al., 1982, 1984; Hunt, 1963; Meyer et al., 1943;

Wilkinson et al., 1963). This is not surprising considering values are determined in populations growing in different climates and under different environmental conditions. Titus and Adams (1979) report a temperature optimum for *V. americana* obtained from University Bay, Madison, WI. to be 32.6 ^{o}C. In laboratory tests (Wilkinson et al., 1963) *V. americana* grew best within a water temperature range of 33 ^{o}C to 36 ^{o}C. In this same study arrested growth occurred below 19 ^{o}C and plants became limp and disintegrated above 50 ^{o}C. The optimum growth temperature was determined under saturating light conditions and is assumed to be a constant value in the model. Bultus, (1987) reports that under non-saturating and low light conditions, temperature optimums may not remain constant values for marine SAVs. He reports lower values during periods of low light conditions relative to higher or saturating conditions. Future work may need to be initiated relating temperature to growth of *V. americana* under the range of conditions specific to the Caloosahatchee Estuary.

Model Calibration

V. americana densities were calibrated to monthly field measurements of shoot and blade density at two Stations within the Upper Caloosahatchee Estuary during the period 1998 – 2001 (**Figure H-3**). Due to limited collection of mass data, calibrations are shown for shoot and blade density. Mass was calibrated to the 1 year of available above ground mass (1998) and was observed for the subsequent years to be consistent with blade and shoot density results (data not shown). The following input data was used: water temperature, secchi disk, water depth, PAR, and salinity (**Table H-2**).

Table H-2: Input Data Summary For Calibration

INPUT DATA	**SOURCE (FREQUENCY)**
Salinity (ppt)	Regression model developed from field data (daily avg.) see **Appendix F** this document
Water Transparency (m)	Field measurement at each station (monthly)
Incident Par	Estero Bay Station with continuos recording (daily avg.)
Water Depth (m)	Field measurement at each station (monthly)
Water Temperature (^{O}C)	Field measurements at each station (monthly)

The four-year data set includes a range of environmental conditions in the Estuary. The first year 1998, produced a large standing crop of *V. americana* and as salinity was relatively low and

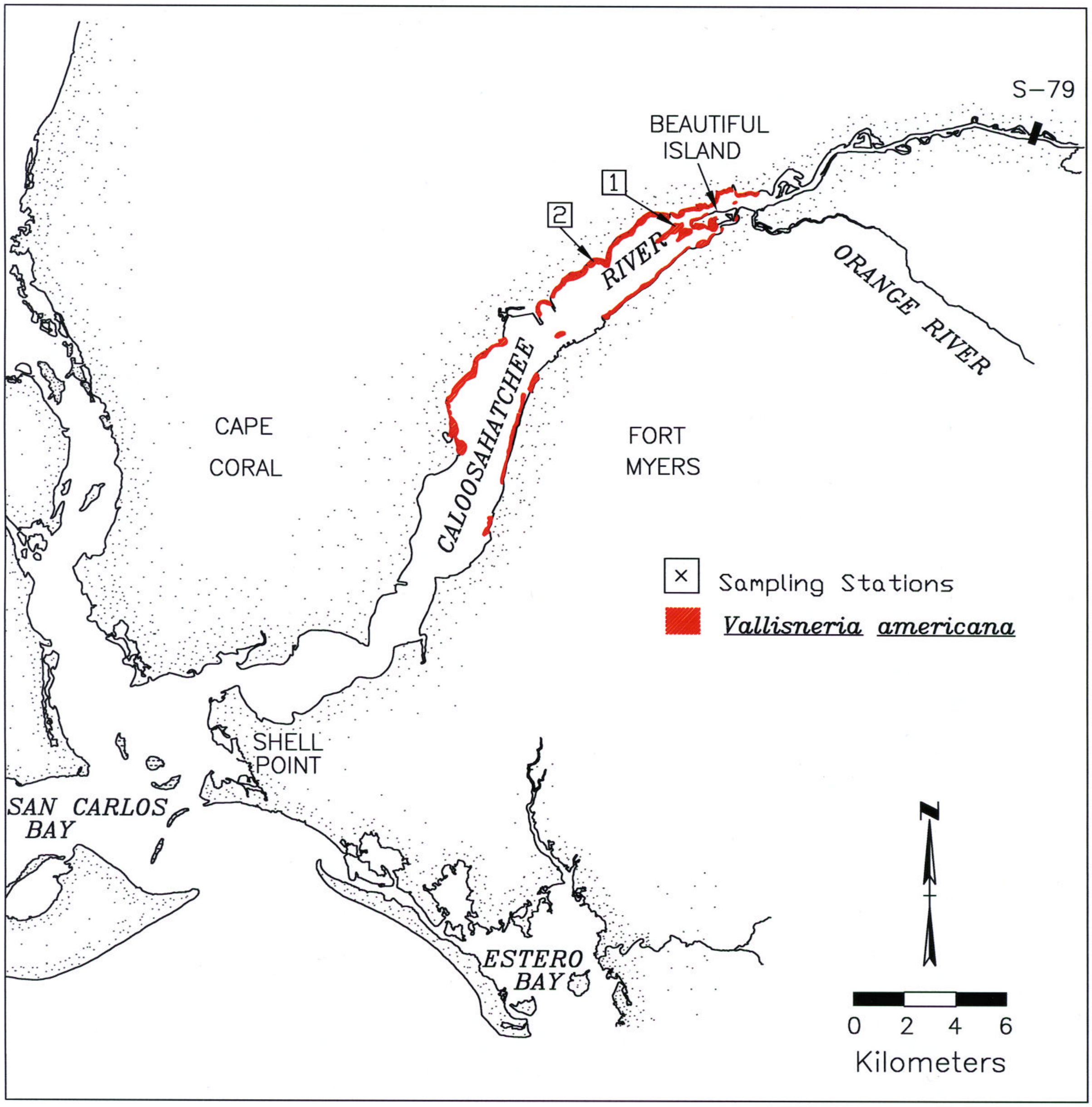


Figure H-3: Calibration Site Locations

water transparency was relatively high, representing ideal conditions for growth (**Figures H-4 and H- 5**). The initial annual densities were low due to reduced growth the previous year. Restricted growth of *V. americana* to varying degrees resulted in the years subsequent to 1998, due to both elevated salinity and reduced water transparency (**Figures H-6, and H-7**).

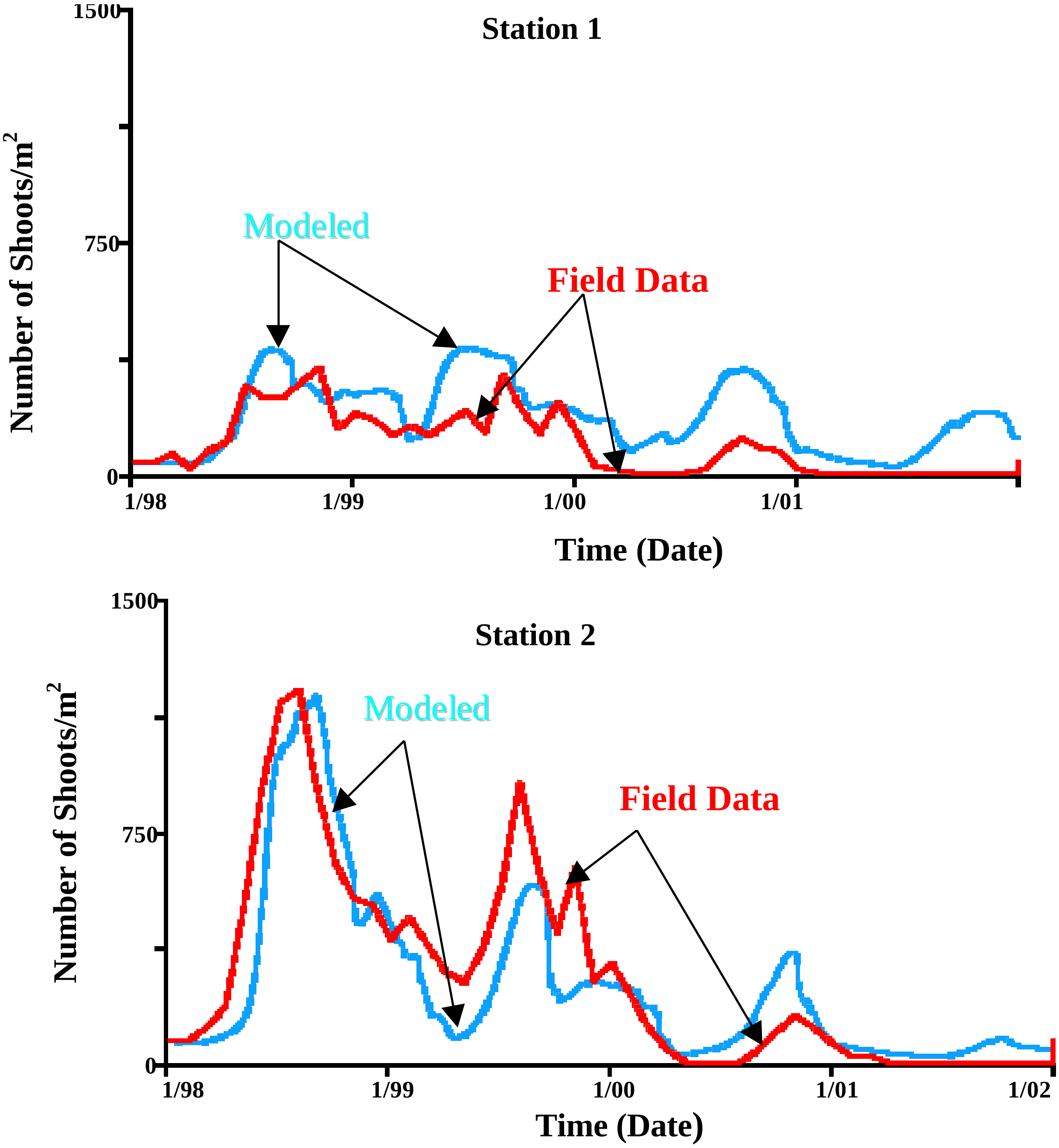


Figure H-4. Results of Calibration - Shoot Densities

In 1999, there was a salinity stress at the beginning of the growing season. Densities decrease slightly then resume growth when salinity returns to a more favorable level. In 2000, the salinity remained fairly low, however algal blooms created light limiting conditions at certain times. These blooms were noted by SFWMD field personal and measured as reduced transparencies in

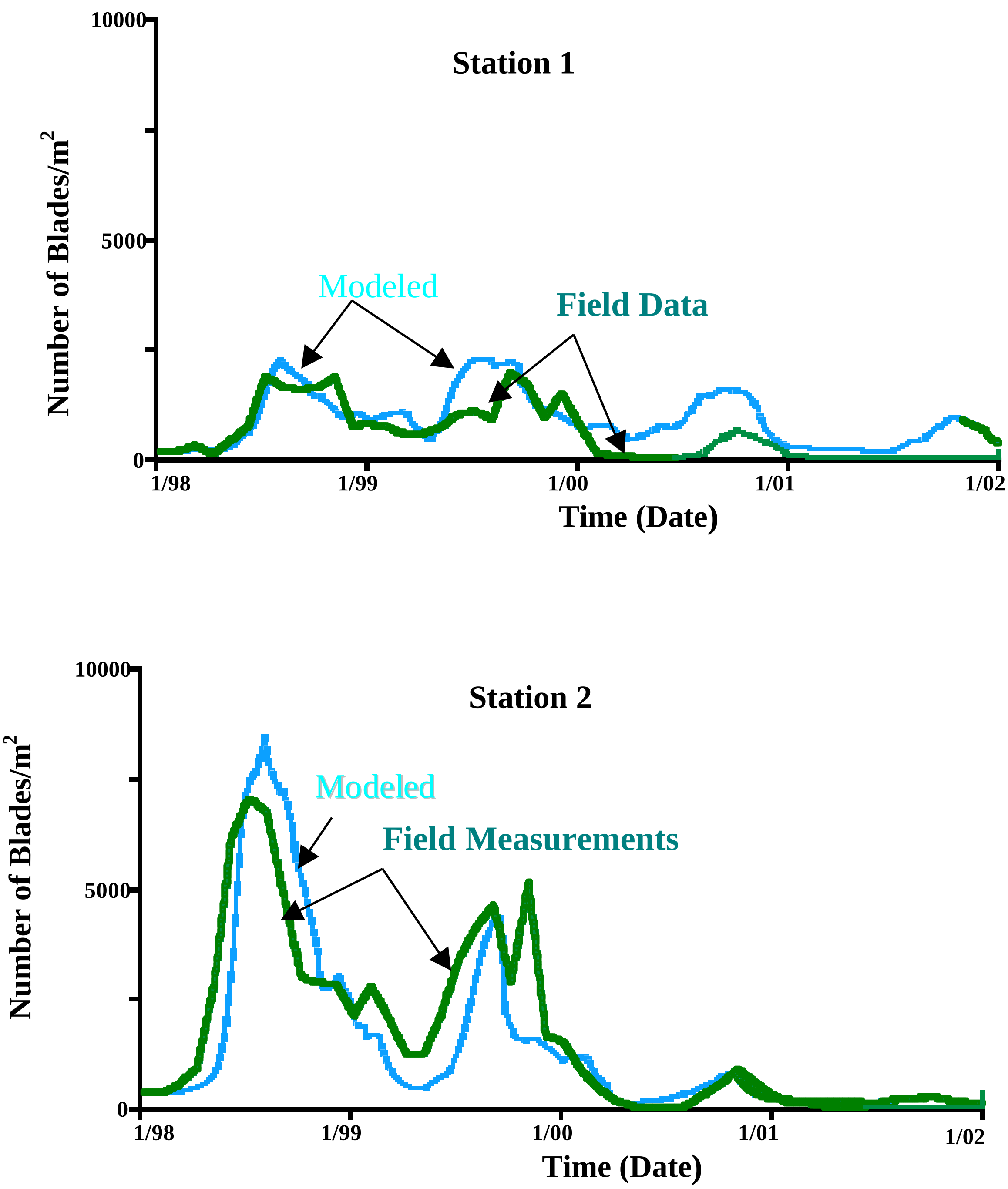


Figure H-5. Results of Calibration - Blade Densities.

the water column. Densities dropped and stayed very low throughout this year. By the end of 2000, *V. americana* was reduced significantly. Due to drought conditions in South Florida high salinity conditions were present throughout most of 2001 and *V. americana* beds did not recover.

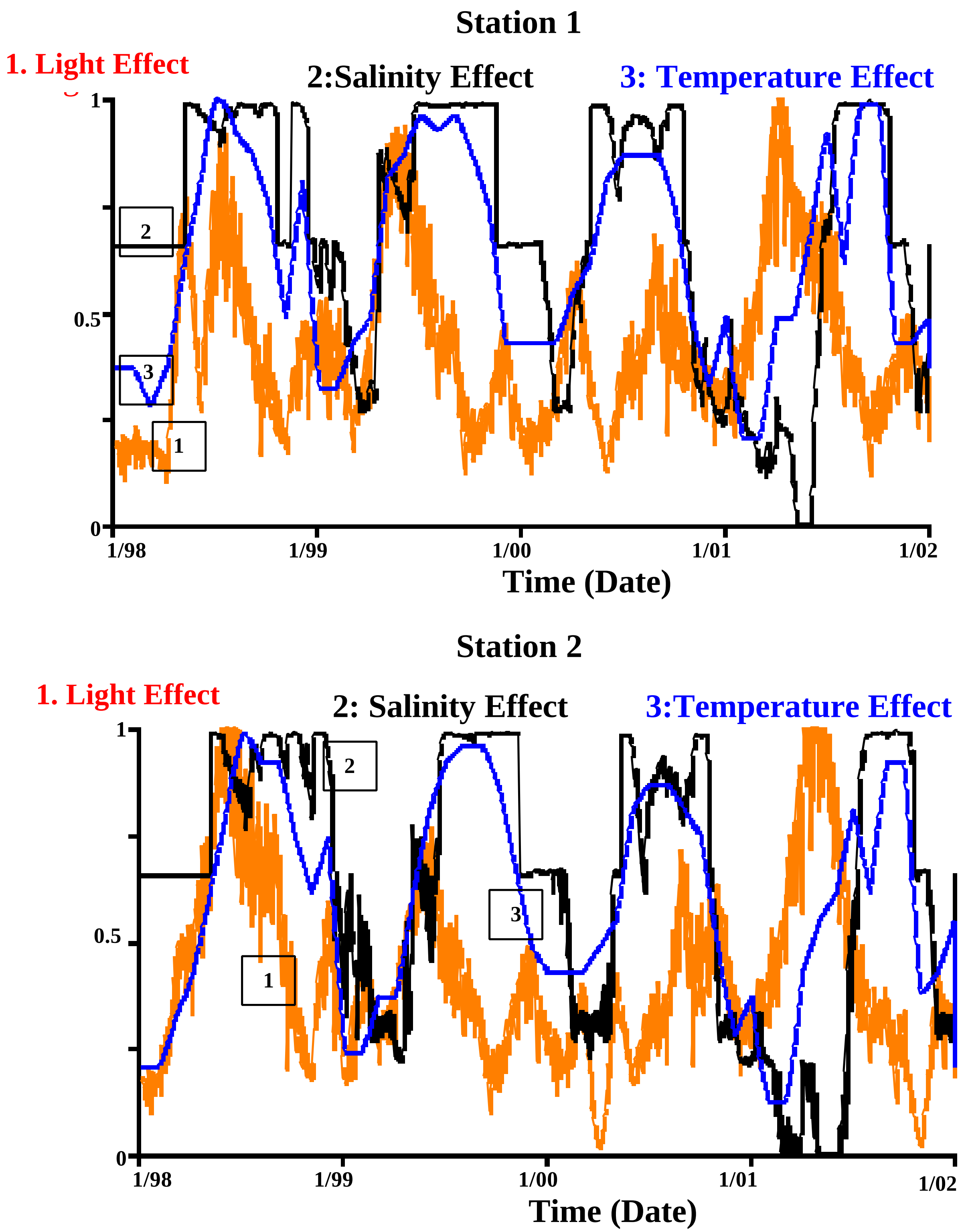
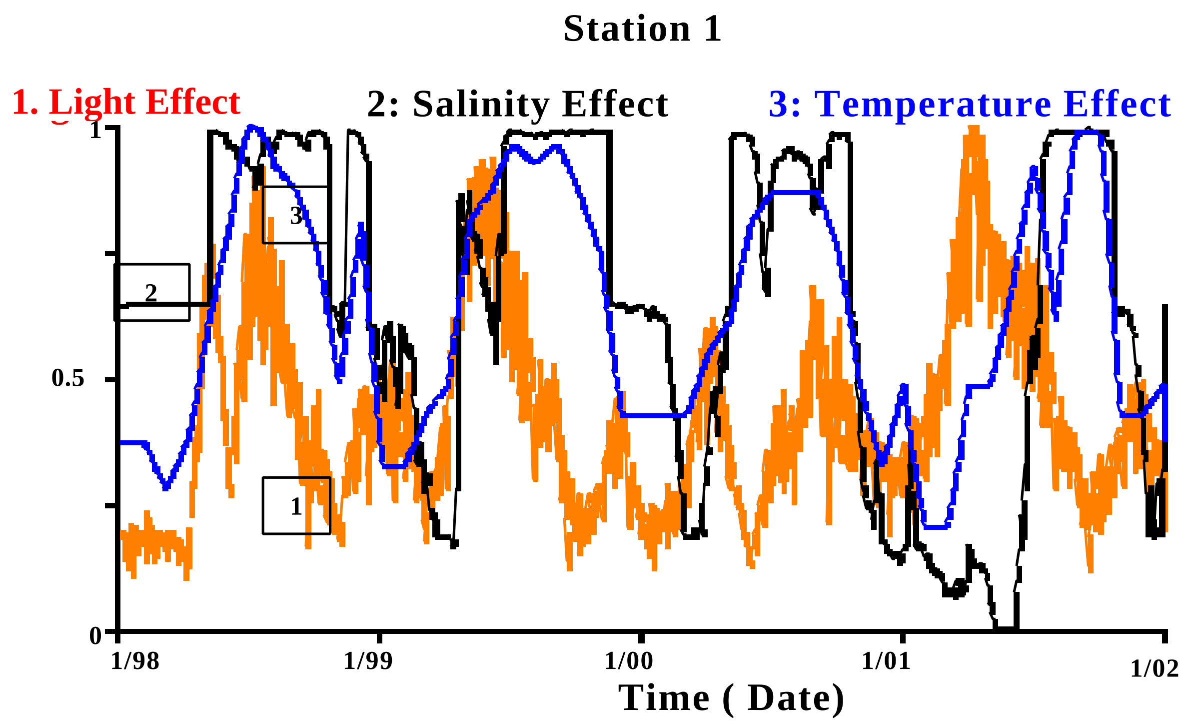


Figure H-6. Results of Calibration - Blade Densities.



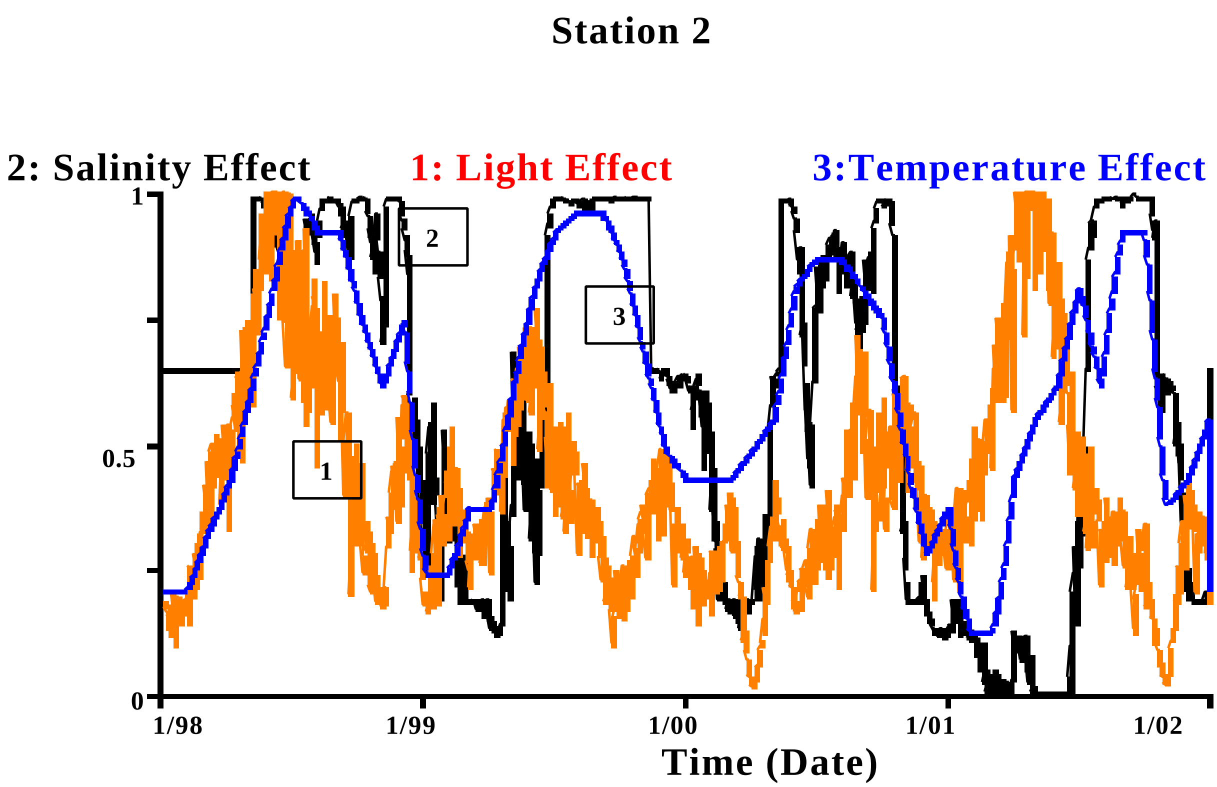


Figure H-7. Results of Calibration- Salinity, Light, and Temperature Effects for Blades.

At Station 1, the modeled computations predict field measurements reasonably well for 1998 and 1999. However the modeled results over-predict *V. americana* densities in the years 2000, 2001. The complete loss of *V. americana* 2001 is not well represented in the model computation at Station 1. At Station 2, the modeled results compare reasonably for all years (1998-2001), with a slight under- estimation of densities occurring in 1999. The calibration data set at Station 2 illustrates the importance of both salinity and light on *V. americana* growth in the Estuary. In 2000 a severe light limitation occurs and although the salinity and temperature become very favorable for growth immediately subsequent to the light restriction, *V. americana* does not recover that year. In 2001, severe salinity conditions are apparent and prevent growth even though light and temperature return to near optimums levels for growth (**Figures H4 to H-7**). Temperatures are below known growth minimums for *V. americana* (Wilkinson, 1963) at Station 2 in the initial two months of the year (14^{o}C) which may also have been inhibitory to growth/ establishment of this year. The temperature calculation does not specify a minimum value and may overestimate density at very low temperatures (**Figures H-6 and H-7**).

Assumptions and Limitations: Calibration

1. Nutrients or other water quality parameters are not represented in the model and assumed to be constant.

2. No epiphytic growth is considered. This would require considerations for nutrient cycling to be added to model.

3. A reduced carrying capacity coefficient (maximum density coefficient) is necessary at Station 1 relative to Station 2. This result indicates that factor(s) other than salinity, light, or temperature may be impacting growth potential at this location. Possibilities include: sediment characteristic(s) such as type, composition, nutritional status, slope, and toxics and/ or physical characteristics such as depth, angle, flow velocity, grazing or other physical disturbance. Future investigation is needed to determine the cause of this difference.

4. It is assumed that a viable seed bank is present for population reestablishment after a significant decline and there is no lag period for growth to commence once

environmental conditions become favorable. No over-wintering buds for *V. americana* have been found in Caloosahatchee Estuary and it is assumed that reestablishment occurs by exclusively by seed germination. Population factors representing seed production or dispersal are not represented in the model.

5. Light availability is calculated based on the light reaching the bottom. This is an appropriate assumption for immature plants with leaves near the bottom. However, this assumption may underestimate available light to larger more mature plants with leaves extending up into the water column.

6. The P/I relationship and associated parameters (i.e. I_k) is assumed to remain the same throughout all possible environmental conditions.

7. The various components that cause changes in water transparency (i.e. color, algal blooms, suspended solids) are not differentiated. The effect is assumed to be the same for all types of light reductions as measured by secci disk depth.

8. Grazing or other potential physical disturbances are not explicitly represented in the model.

9. The effect of temperature changes on productivity is assumed to remain the same throughout all possible environmental conditions (such as salinity or light changes).

10. The temperature minimum is not explicitly represented in the temperature formulation and may overestimate growth if temperatures fall below the minimum growth temperatures.

Sensitivity Analysis

Input Data

The quality, type, location and variability associated with the input data are important considerations when interpreting model results. Field measurements should be used whenever possible and the error associated with obtaining and processing the measurements should always be considered. Unfortunately, creating input files using field data from the locations under consideration is not always possible. This may be the case when: there is limited field data in the area of interest, for long-term simulations, and for future scenario analysis. Developing approximations for input data during years when field data is not available is often necessary. However, this introduces an additional source of error in the analysis. The potential impact of using a form of input approximation (averaged data input files) verses field data during the 4-year calibration period is illustrated by substituting the calibration files with the following:

- daily salinity input calculated from a regression model (**Appendix F**),
- 4-year water transparency averaged input files,
- 4-year temperature averaged input files.

In the latter two instances, the averaged input file was developed by averaging the four years calibration data to create one "average year" input file.

Parameters

The sensitivity of input parameters is an additional factor to consider. Constant values obtained from the literature are used in both the temperature and light functions. These values were obtained under defined experimental conditions and do not necessarily represent the range of conditions possible in the Caloosahatchee Estuary. Sensitivity analysis for the following parameters are provided:

- Light saturation (I_k),
- Optimum temperature,
- Maximum temperature,
- Q10 coefficient used in temperature equation.

Sensitivity Analysis Discussion

For discussion purposes blade densities are specifically discussed in the sensitivity analysis. The same analyses were performed for shoot densities with comparable results (data not shown.)